should be possible by using a few hundred mW of 1.06-μm pump power from a cw Nd:YAG laser. Such a tunable infrared source would be useful not only for diagnostic studies of semiconductor laser materials, but also for the measurement of fiber properties in a spectral range that is considered very promising for future optical fiber communication links.

In conclusion, we have demonstrated a high-efficiency, stable, and continuously tunable cw Raman oscillator. Several applications and advantages of such an oscillator have been discussed, indicating its potential as a source of tunable coherent radiation both in the near infrared and the visible.

The authors thank W.G. French, G.W. Tasker, and J.B. MacChesney for helpful discussions on fiber preform fabrication.

[1]R.H. Stolen and E.P. Ippen, Appl. Phys. Lett. 22, 276 (1973).
[2]G.W. Tasker and W.G. French, Proc. IEEE 62, 1278 (1974); M. Horiguchi and H. Osanai, Electron. Lett. 12, 310 (1976)
[3]E.P. Ippen, Appl. Phys. Lett. 16, 303 (1970).
[4]R.H. Stolen, E.P. Ippen, and A.R. Tynes, Appl. Phys. Lett. 20, 62 (1972).
[5]K.O. Hill, B.S. Kawasaki, and D.C. Johnson, Appl. Phys. Lett. 29, 181 (1976).
[6]J. Stone, Appl. Phys. Lett. 26, 163 (1975).
[7]D. Gloge, Appl. Opt. 10, 2252 (1971).
[8]R.H. Stolen, Proceedings of the Conference on Light Scattering in Solids, Campinas, Brazil, 1975 (unpublished).
[9]E.P. Ippen and R.H. Stolen, Appl. Phys. Lett. 21, 539 (1972).
[10]K.O. Hill, D.C. Johnson, and B.S. Kawasaki, Appl. Phys. Lett. 29, 185 (1976).
[11]No concerted effort was made to reduce the intracavity losses of the present resonator. With better optics, antireflection-coated surfaces and a different resonator configuration, it should be possible to reduce the round-trip loss to less than 5 dB.
[12]Such sources can in turn be intracavity doubled to yield high average power ultraviolet powers in the 2500—2700-Å region, a spectral region of immense interest for the study of biological molecules.

Generation of single synchronizable picosecond 1.06-μm pulses

I. V. Tomov, R. Fedosejevs,* and M. C. Richardson

National Research Council of Canada, Division of Physics, Ottawa, K1A OR6, Canada
(Received 28 September 1976)

We report the generation of reliable synchronizable single mode-locked 1.06-μm pulses with pulsewidths variable from 1.3 ns to the spectral transform limit of 15 ps.

PACS numbers: 42.55.Px, 42.60.By

In an earlier publication we have reported the development of the first synchronizable actively mode-locked Nd:glass ring laser.[1] This system displayed considerable advantages over conventional passively mode-locked Nd:glass lasers in terms of reproducibility and the capacity to precisely synchronize a single high-power subnanosecond pulse to an arbitrary external event. Although measurements of the pulse duration were limited by the response of the detection system (~600 ps), it was expected that the active modulator would limit the pulse width to durations significantly greater than that typically achieved with passively mode-locked Nd:glass systems. In this paper we describe detailed temporal and spectral characteristics of this system, and in particular report its further development for the generation of diffraction-limited, approximately transform-limited, picosecond pulses. This is achieved through the use of an additional pulse-shortening element, a saturable dye cell. A similar approach has been adopted by Krivoshchekov *et al.* in mode locking a ruby laser.[2] We also show that the incorporation of this element in the resonator permitted unidirectional travelling wave operation of the ring laser.

The laser system, and the various diagnostics employed to characterize it, are shown schematically in Fig. 1. In order to obtain synchronizable mode-locked operation, two electro-optical elements are incorporated in the ring resonator.[1] On the commencement of oscillation, the initial noise pulse is modulated at the resonator frequency by a KD*P active modulator (PC_2) to which is applied a 60-MHz sine wave voltage providing up to 40% loss modulation. The second electro-optic element (PC_1), a triple-electrode Pockels cell, is situated between two dielectric polarizers (PI_1 and PI_2) providing the capability for both dynamic Q control during the buildup of the pulse and for synchronous switch-out of the single pulse. The dynamic Q control consists of a double-step voltage pulse applied to one segment of PC_1 which maintains partial transmission in the Pockels cell for ~1.8 μs during the initial buildup of the pulse; after which it is switched to full transmission. In the present studies, the switch-out pulse applied to the second segment of PC_1 is provided by a laser-triggered spark gap (LTSG) activated by the birefringence-induced leakage radiation reflected from PI_2. Single transverse mode operation was controlled by aperture A. Also included in the resonator is a 1.4-

Copyright © 1977 American Institute of Physics

Downloaded 31 Oct 2003 to 132.170.162.242. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp

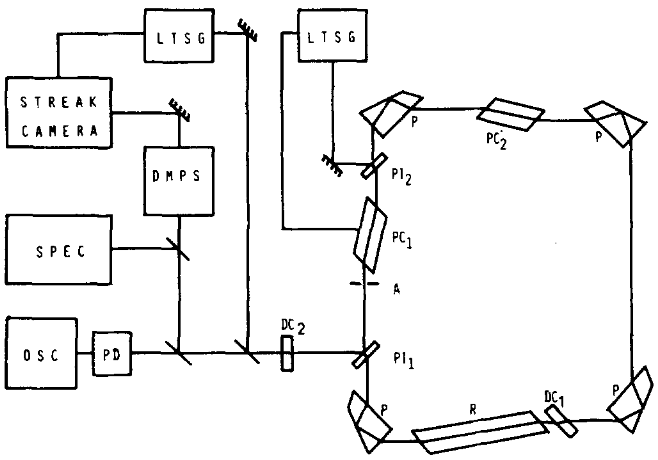

FIG. 1. Schematic diagram of the actively mode-locked Nd:glass ring laser and diagnostics used to characterize its output. Legend: P: Pellin-Brocca prisms; R: Nd:glass (Schott LG55) laser rod; PC_1: three-electrode double Pockels cell; PC_2: active KD*P modulator; PI_1, PI_2: dielectric polarizers; A: aperture; DC_1, DC_2: saturable dye (Kodak 9740) cells; LTSG: laser-triggered spark gaps; PD: fast biplanar photodiode; DMPS: picosecond pulse delay and multiple-pulse illuminating system.

mm-thick saturable absorber (Kodak 9740) cell, DC_1, situated in close proximity to the 20-cm-long Nd:glass rod as shown. The use of this element provides for effective pulse shortening, while preserving synchronizability, and, induces unidirectional travelling wave operation in the counterclockwise direction.

The single-pulse output passes through an additional saturable absorber (DC_2) with a small-signal transmission of 5% giving a pulse intensity contrast ratio of $>10^3$. Temporal measurements of the pulse duration were made with a fast-biplanar photodiode-oscilloscope combination having a temporal resolution of 600 ps, and an ultrafast infrared sensitive (S1 photocathode) streak camera, activated by a laser-triggered spark gap (LTSG), and having a theoretical temporal resolution of ~13 ps. Pulse spectra were recorded with a $\frac{3}{4}$-m Czerny-Turner grating spectrograph with a dispersion of 10 Å/mm in conjunction with an infrared-sensitive image intensifier.

Without a saturable absorber in DC_1 the temporal profile and spectrum of the pulse was studied as a function of the depth of modulation induced by the active modulation. In this case the initial Q-control step pulse permitted 70% transmission through the Pockels cell, PC_1. From Fig. 2, it can be seen that the pulse duration changes from 1.3 ns to ~200 ps with variation of the modulation index θ_m from 0.2 to 0.7. In this case the modulation index is defined by

$$\theta_m = \frac{\pi}{2}\frac{V}{V_{\lambda/2}}, \qquad (1)$$

where V is the peak voltage applied to the AM modulator and $V_{\lambda/2}$ is its half-wave voltage. The maximum depth of modulation was limited by the available rf driving power. When low depths of modulation were used ($\theta_m < 0.2$), poor mode locking resulted due to resident birefringence in the electro-optic crystal. Pulses shorter than 500 ps were measured with the picosecond

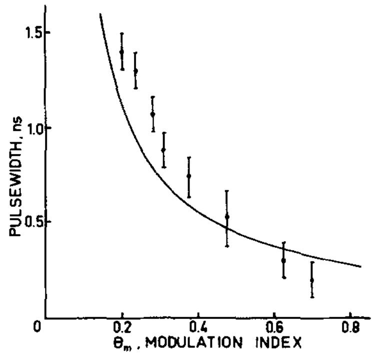

FIG. 2. Mode-locked pulse duration as a function of modulation index. The points represent measured values and the solid curve represents the pulse duration predicted by simple transient pulse buildup theory.

streak camera, and, as can be seen from Fig. 3(a), reveal the existence of substructure in the pulse [Fig. 3(b)]. The corresponding spectrum of these pulses, Fig. 3(c), has a width (FWHM) of ~4 Å, which would be compatible with the existence of ~8-ps duration substructure in the pulse.

The observed variation of pulse width as a function of depth of modulation is in approximate agreement with the simple theory of the transient buildup of mode-locked pulses[3] which predicts a pulse duration (FWHM) for the present system of

$$\tau_p = \frac{1}{\pi\theta_m f_m}\left(\frac{\ln 2}{M}\right)^{1/2}, \qquad (2)$$

where M is the number of resonator transits during the buildup of the pulse, f_m is the modulator frequency, and θ_m is the modulation index. In Fig. 2, τ_p is plotted for

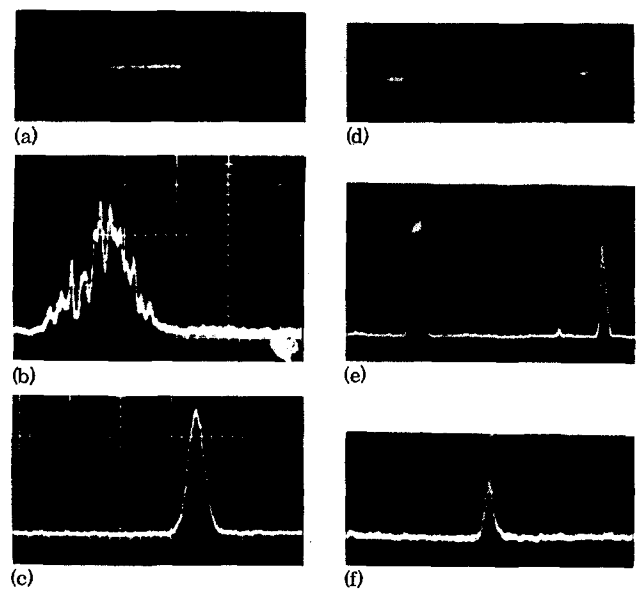

FIG. 3. (a) Streak picture of the 1.06-μm pulse with active modulation only. (b) Densitogram of the streak picture above (~100 ps/div). (c) Corresponding spectrum of the 1.06-μm pulse (12 Å/div). (d) Streak picture of the 1.06-μm pulse with active modulation and saturable dye cell. (e) Densitogram of the streak picture above (~100 ps/div). (f) Corresponding spectrum of the shortened 1.06-μm pulse (12 Å/div).

Downloaded 31 Oct 2003 to 132.170.162.242. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp

$M=400$, corresponding to a total buildup time of 3.33 μs, and $f_m = 6\times 10^7$ Hz. Although the measured dependence of the pulse duration on modulation index is of the general form of Eq. (2), it is noted that τ_p falls off more rapidly with increasing θ_m than predicted. However, the existence of the substructure evident in the streak camera recording indicates that the buildup of these pulses is more complicated than that described by this simple model.

Further shortening of the pulse was achieved for maximum active modulation, with the introduction of a weak dye solution in the cell DC_1 having a small-signal transmission of 80%. In this case the initial Q-step transmission of the Pockels cell PC_1 was increased to 84%, giving an overall initial pulse transmission of 67%. Thus the total buildup time was similar to that required in the case when no pulse shortening was induced, ~3.3 μs. A typical streak photograph of the single pulse is shown in Fig. 3(d). With the use of a delay and multiple-pulse system (DMPS) several samples of the single pulse, each separated by 545 ps, illuminate the streak camera. The figure shows the streak camera record of two pulses from the DMPS having a difference in intensity of 60%. As can be seen the more intense pulse is at the saturation level of the detection system. The resulting densitogram of the time-resolved record of the less intense pulse, Fig. 3(e), indicates a pulse duration of ~15 ps. It is apparent from the corresponding single-pulse spectrum, Fig. 3(f), which has a width (FWHM) of ~2.4 Å, that the pulse is approximately transform limited. The energy in the shortened pulse was ~0.2 mJ.

The saturable absorber, DC_1, performs a second function in inducing unidirectional travelling wave operation within the resonator. By placing the saturable absorber in close proximity to the Nd:glass rod, as shown in Fig. 1, counterclockwise travelling wave operation is favored over clockwise operation. During the period of linear gain in the rod, and linear loss in the absorber, the clockwise and counterclockwise pulses build up with equal intensity and are forced to coincide in the active modulator. However, the dye cell is situated at a position in the resonator where the clockwise pulse has less intensity than the counterclockwise pulse and where the two pulses do not coincide. Thus as the two pulses achieve intensities sufficient to induce nonlinear transmission in the dye, the counterclockwise pulse passes through the latter with greater intensity, suffers less loss, and consequently gains preferentially in amplitude over the clockwise pulse. When operating with a low net gain in the resonator the counterclockwise pulse depletes the gain of the rod inhibiting the growth of the clockwise pulse. This results in better than an order of magnitude difference between the final intensities of the counterclockwise and clockwise pulses. Detailed experimental and theoretical studies of this particular aspect of the laser system are at present in progress.

In conclusion we have reported the principal characteristics of an actively mode-locked picosecond Nd : glass laser system providing a well-stabilized synchronizable single transform-limited pulse output which is diffraction limited. It should find application in a number of areas of investigation where a high-intensity picosecond laser pulse is required to be in precise synchronism to an arbitrary external event. It has already been applied to preliminary optical diagnosis of plasmas created by high-power CO_2 laser pulses.[4]

The authors wish to gratefully acknowledge the expertise of W.J. Orr in the development of the laser system and the continuing experimental assistance of W.P. Kennedy, K.E. Leopold, P. Burtyn, and G.A. Berry throughout these studies.

*Work performed in partial fulfillment of Ph.D. degree of the University of Toronto.

[1]I.V. Tomov, R. Fedosejevs, M.C. Richardson, and W.J. Orr, Appl. Phys. Lett. 29, 193 (1976).
[2]G.V. Krivoshchekov, N.G. Nikulin, and V.A. Smirnov, Sov. J. Quantum Electron. 5, 1096 (1976).
[3]D.J. Kuizenga, D.W. Phillion, T. Lund, and A.E. Siegman, Opt. Commun. 9, 221 (1973).
[4]R. Fedosejevs, I.V. Tomov, and M.C. Richardson, Bull. Am. Phys. Soc. 21, 773 (1976).

Downloaded 31 Oct 2003 to 132.170.162.242. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp